Fire Technology
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https://doi.org/10.1007/s10694-025-01699-w

Can ''Fire Safe'' Cigarettes (FSCs) Start Wildfires?

*Sara McAllister**, *RMRS Missoula Fire Sciences Laboratory, USDA Forest Service, Missoula, MT, USA*
Stephen Williams, Bureau of Alcohol, Tobacco, Firearms and Explosives, Billings, MT, USA
Ian Grob, RMRS Missoula Fire Sciences Laboratory, USDA Forest Service, Missoula, MT, USA

Received: 3 September 2024/**Accepted:** 2 January 2025

Abstract. Over the last 20 years, all states within the US have required all cigarettes sold to be ''fire safe'' or ''fire standards compliant'' meaning that they must pass ASTM standard E2187. Though these cigarettes are designed to self-extinguish, there have been recent studies suggesting that these ''fire safe'' cigarettes (FSCs) can still ignite mattresses and other furnishings, but there has been no guidance for fire investigators whether FSCs can ignite natural fuels, such as duff and needles, that can be the source of a wildland fire. This work sets out to investigate whether FSCs can indeed be the ignition source of wildland fuels. Experiments were conducted by placing ''fire safe'' cigarettes burned a fixed length (1 cm) onto fuel beds of two surrogate fuel types placed at the outlet of a wind tunnel and under a halogen lamp to mimic a sunny day. The fuel beds consisted of either a bed of partially chopped pine needles or a layer of whole needles on top of a layer of peat. Five replicates with three wind speeds were tested. Mass loss rates of the fuel beds were recorded, and the experiments documented using both a visual and infrared camera. In nearly every case, smoldering ignition was seen that sustained propagation and spread well away from the cigarette, even when the cigarette appeared to self-extinguish. These results clearly indicate that ''fire safe'' cigarettes can indeed still start wildland fires, particularly in dry and windy conditions.

Keywords: Wildland fire, Ignition, Fire safe cigarettes, Reduced ignition propensity

1. Introduction

Cigarettes have long been acknowledged to be an ignition source of fires, both in the built environment and in the wildlands. The high incidences of property losses, injuries, and deaths from fires in the US throughout the 20th century led to the development of ''Fire Safe'' Cigarettes (FSCs) [1]. Though the prevalence of smoking is declining, smoking is still the reported cause of 2% of residential fires, a figure that has not changed since the introduction of FSCs [2]. Fires started by

*Correspondence should be addressed to: Sara McAllister, E-mail: sara.mcallister@usda.gov

Published online: 07 February 2025

smoking are still one of the leading causes of death in residential fires [2, 3]. Between 2010 and 2020, smoking was still reported as the cause of 1700 wildfires per year on average in the United States, burning an average of 9000 ha/year [4]. There is thus still a clear need to understand this ignition source.

As reviewed in detail in [1], the passage of the Cigarette Safety Act in 1984 [5] initiated research to determine the feasibility of developing cigarettes and ‘‘little cigars’’ with a reduced ignition propensity. A Technical Study Group was formed that researched the burning mechanisms of a cigarette and ways to control it. Dr. Richard Gann of the National Institute of Standards and Technology (NIST) (called the National Bureau of Standards (NBS) at the time) led this Technical Study Group, which comprised of others from the Consumer Product Safety Commission, National Fire Protection Association, Federal Emergency Management Agency, Federal Trade Commission, National Cancer Institute, representatives of the tobacco and furniture industries, as well as others [6]. The final report of the Technical Study Group to Congress [6] (and further elaborated on in an internal publication [7]) concluded that it is indeed both technically and economically feasible. The findings indicated that low tobacco density, reduced cigarette circumference, and low paper permeability significantly reduced the ignition likelihood, particularly when these characteristics were combined [8]. This report also recommended the development of a standardized testing methodology to fairly compare the ignition propensity of different cigarette designs and brands. As a consequence, the Fire Safe Cigarette Act of 1990 [9] required NIST to develop such a standard test to evaluate the ignition propensity of cigarettes which could also be used to set a minimum performance criterion. In 2002, ASTM Standard E2187 [10] was released following NIST suggested procedures [11]. This standard considers cigarettes to be ‘‘fire safe’’ (technically referred to as Reduced Ignition Propensity, RIP) if no more than 10 of 40 cigarettes placed on a filter paper substrate burn their full length. In 2000, New York became the first state to pass a law (N.Y. Executive Law § 156C, effective 2004) requiring all cigarettes sold to be ‘‘fire safe,’’ and subsequently, all 50 states and the District of Columbia have followed. Similar requirements (for example ISO 12863 [12]) are in place in Australia, Canada, Iceland, South Africa, and all member states of the European Union [13]. Commercially available ‘‘fire safe cigarettes’’ (FSCs) commonly are wrapped with paper that has bands of lower permeability and diffusivity that are meant to allow the cigarette to self-extinguish when not actively drawn [1, 14].

Note that there is a difference in terminology between the technical documentation and colloquial usage by both the public and lawmakers. Technical documentation refers to these cigarettes as ‘‘reduced ignition propensity’’ whereas the public and lawmakers tend to use the phrase ‘‘fire safe cigarettes’’ (for e.g. [9]), but the terms both reference the same product. Here, as elsewhere, the terms are used interchangeably. However, ‘‘reduced ignition propensity’’ is the technically more accurate description because 25% cigarettes are allowed to ignite the substrate in the standardized tests and still qualify. However, the acronym ‘‘RIP’’ does not sit well in the American vernacular and is not as marketable as ‘‘fire safe.’’ Between the marketability and the simplicity of the ‘‘fire safe’’ description, it is not surprising that this is the terminology most often heard, even among fire investigators. This obviously leads to misunderstandings of the fire potential of cigarettes by the public, lawmakers, and fire investigators.

Despite the intention of a FSC preventing accidental fires, studies on whether the tendency to self-extinguish translates to a real reduction in substrate ignition have shown mixed results. For example, in [15], experiments were conducted with 50 common fabrics and 11 commercial cigarette brands. No statistical difference was found in ignition probability between the six brands classified as RIP and the five that weren't. Similarly, when cigarettes constructed with 25 different combinations of tobacco density, circumference, paper porosity, and paper citrate levels were tested on six fabric types in [16], mixed results were seen, where some cigarette features resulted in fabrics igniting either more or less frequently. For example, reducing the paper porosity (a common feature of modern FSCs) reduced ignitions on duck fabric, but increased ignitions on light areal density commercial fabric. Experiments with RIP and non-RIP cigarettes on a variety of fabric and fill materials of Japanese-style bedding revealed that the material type was more indicative of an ignition than cigarette type [17]. Testing with RIP and non-RIP cigarettes in wastebaskets with crumpled office paper indicated that both regularly resulted in flaming ignition of the paper [18]. When testing four different combinations of mattresses and mattress pads in [19], no difference between RIP and non-RIP cigarettes was found, concluding that "whether a cigarette – RIP or non-RIP – burned its full length or extinguished before burning its full length was not predictive of smoldering behavior on the substrates."

The main concern of this work, however, is wildland fuels. This is obviously related to the potential to ignite a wildland fire, but increasingly can be related to residential building fires as well. Increasing smoking bans have pushed more smokers outside, resulting in more home ignitions from smoking being initiated on porches or balconies in potted or natural vegetation [3]. The early work on the ignition of wildland fuels by cigarettes is reviewed in [20] and [21]. These early works highlight the dependency on fuel type, moisture content, contact area between the cigarette and fuel, and wind velocity. The most readily accessible of these earlier works is that by Countryman [22–24]. In [23], Countryman described that a dropped cigarette would not ignite natural standing grass because it tended to be suspended in the very open vertical blades and not reach the denser litter layer below. A dropped cigarette would thus only contact one or two blades of grass. If the cigarette was deliberately placed in the litter layer, ignition was possible. Countryman then conducted experiments with beds of chopped grass, sorted into three size classes and with different moisture contents and cigarette orientations relative to the wind. In his tests, the finest-sized fuel particles (< 2.5 mm or 0.1″) readily ignited up to moisture contents of 10%. The medium-sized particles (2.5–5 mm or 0.1–0.2″) showed more erratic ignition patterns, and the larger particles (19–38 mm or 0.75–1.5″) didn't ignite at all. Deeper fuel beds and tests with the cigarette tip pointed into the wind ignited more readily. The importance of wind, fuel moisture content, and cigarette contact with the fuels was confirmed more recently by Dainer in [25].

Unfortunately, it appears that very little work examining the ignition potential of wildland fuels by cigarettes has been conducted with FSCs. A recent review

Figure 1. The fuel sample holder was made of wire mesh and was supported 1.3 cm above the weighing platform by strips of cement board. The load cells can be seen underneath. The samples were placed at the outlet of a wind tunnel.

highlights this discrepancy and points to the work on the ignition of wildland fuels being largely out-of-date [21]. A couple of recent studies have been conducted in China [26, 27], but it is unclear whether the cigarettes used were FSCs. Recently, Viegas et al. proposed a conceptual model and conducted some experiments with both FSCs and non-FSCs in a straw fuel bed [28]. They only considered flaming ignition but did not see a major difference in the ignition probability between RIP and non-RIP cigarettes. If anything, their Figure 15 implies a slightly *greater* ignition probability with the RIP cigarettes in straw fuels. Though testing was somewhat limited, some experiments by Henriksen et al. suggest that RIP cigarettes can still ignite wildland fuels, even at relatively high relative humidities [29]. However, there is some indication that the switch to FSCs has reduced the number of smoking-caused wildfires in the U.S. by 23% [30]. This gap in the literature has resulted in a lack of clear guidance for fire investigators whether this is still a possible ignition cause [21], possibly leading the investigator to dismiss evidence of a burning cigarette in their investigation. The notion that cigarettes are “fire safe” by the public may also contribute to careless usage and disposal behaviors. There is a clear need to firmly establish that fire safe cigarettes can start wildland fires, both for public information and for supportive documentation for fire investigators, which is the goal of this work.

2. Methods/Experimental

2.1. Apparatus and Fuels

Fuels were placed in wire mesh holders that are 25 cm × 25 cm × 2.5 cm deep (Figure 1). The mesh used was 304 stainless steel, 16 × 16, with a wire diameter of 0.4 mm (0.016″) and 55% open area. The sample holder was supported 1.3 cm above the surface of the weighing platform using strips of cement board to allow for air flow under-

Figure 2. A halogen work lamp was suspended above the fuel to mimic solar radiation. Here you can also see the GoPro camera and the whole of the wind tunnel.

neath (Figure 1). The weighing platform was a thin aluminum sheet (30.5 cm in diameter) covered with several sheets of ceramic paper to prevent any heat transfer to the load cells underneath. Three load cells (816 g capacity, calibrated to + / − 0.1 g) connected to a Campbell Scientific[1] CR5000 data logger recorded the change in mass at 1 Hz (1 sample per second). A halogen work light was suspended above the fuel samples during the experiments to simulate solar heating (Figure 2). The heat flux provided was measured in the middle of the sample and at four cardinal directions to estimate the uniformity. The average heat flux provided by the light was 810.2 W/m^2 with maximum deviation of 3.5%. Typical values of solar irradiance vary with atmospheric conditions, time of day, latitude, elevation, and season, but are generally to be considered to be around 1 kW/m^2 at noon at sea level on a clear day (for example [31–33]), so the irradiance provided by the lamp was a reasonable approximation for summer solar heating in mid-latitudes. The weighing platform and light were placed at the outlet of a wind tunnel with cross section of 25 cm × 9.5 cm. The wind tunnel was 60 cm long and produced laminar air flow up to 1.8 m/s (Figure 2, see [34–36] for more detail). The height of the sample holder was such that the top of the fuel was at the same height as the bottom of the wind tunnel (Figure 1). Each test was recorded using a GoPro Hero 3 + camera, a Sony HXR-NX80 visual camera, and a FLIR T650SC (emissivity equal to 1 and 30 frames/sec) IR camera (see Figure 3). Still photos were taken with a Nikon D-700 camera with 60 mm micro and 105 mm macro lenses and Nikon D-7500.

Two fuel beds were considered. After some scoping experiments, the findings of Countryman [23] were confirmed that it was difficult to maintain enough contact with whole thin fuels such as grass and needles and that some fine material was required. The first fuel used here was a bed of lightly chopped long-leaf pine needles (Figure 4). The needles were commercially sourced from the southeastern U.S and were nominally 20–25 cm (8–10 in) long, however they tended to curl when

[1] The use of trade names is provided for reader information and does not imply endorsement of any product or service by the U.S. Department of Agriculture or Bureau of Alcohol, Tobacco, Firearms and Explosives.

Figure 3. IR and visual cameras were also used to record the experiments.

Figure 4. Cigarette nestled into the chopped pine needle fuel.

dried. They were chopped using a Thomas-Wiley Laboratory Mill Model 4 using a 6 mm (¼”) hardware cloth for a screen. The sample holder was filled to its entire depth with approximately 131.3 g of chopped needles. A small divot was created in the middle to ensure that the cigarette settled into the fuel with as much contact as possible. The cigarettes did still largely rest on the surface of the fuels, which resulted in greater convective heat losses than if the cigarette were buried in the fuel. To get an idea of the distribution of the particle sizes used, three subsamples of approximately 50 g of chopped needles were sieved. The following sieves were used: ¼” (6.3 mm), 0.185″ (4.7 mm, #4 mesh), 0.131″ (3.3 mm, #6 mesh), 0.0787″ (2.0 mm, #10 mesh), 0.0469″ (1.2 mm, #16 mesh). The subsamples were added to the stacked sieves and placed on a mechanical shaker for 20 min. The mass of needles in each sieve was then weighed, and the total amount was reweighed to assess if particles were lost during the procedure (such as by falling out while moving and pouring).

Figure 5. Cigarette placed into peat/whole needle bed, ensuring contact with peat below.

Figure 6. Drawing down the cigarette to 1 cm, pre-marked with a red line.

The other fuel bed consisted of a base layer of Canadian sphagnum peat moss that was also passed through the same Wiley Mill with hardware cloth to break up the large clumps. This base peat layer was approximately 64.8 g and nominally 1 cm deep, spread as evenly as possible in the sample holder. Note that due to the openness of the screen used as a sample holder, very fine or powdery material would fall out and thus was not part of the peat fuel layer. Above this peat base layer, approximately 16.1 g of whole long-leaf pine needles were arranged to lay as evenly and flat as possible (Figure 5). This quantity of needles was chosen as it resulted in the level of the needles being approximately even with the top of the sample holder, however, due to this needle length, the needles were quite sparse with not a lot of continuity. A path through the needles was made for the placement of the cigarette to ensure contact with the peat layer. In these cases, the cigarette was partially sheltered from the wind by the needles which may have reduced the convective heat losses slightly compared to the chopped needle beds.

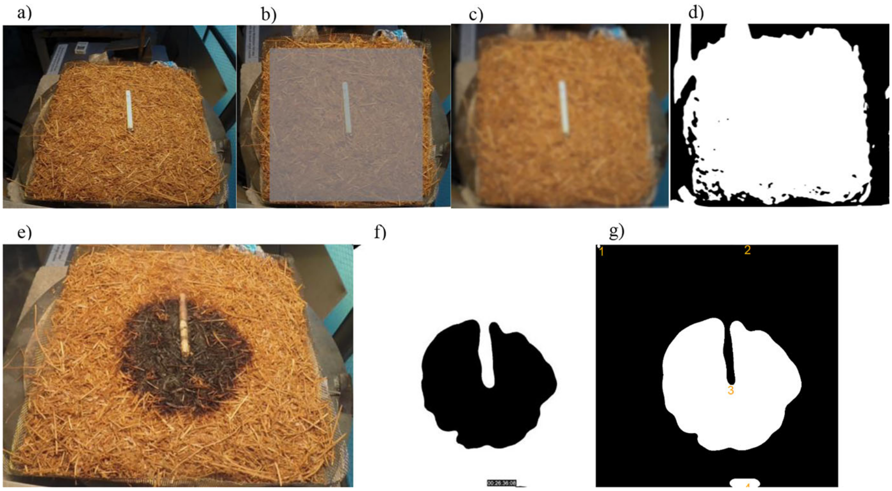

Figure 7. Image analysis process to estimate spread rate. Images in the top row show steps taken using Adobe Premier (at test initiation). Images in the bottom row show steps taken using RStudio (at 26:36 into same test). (a) The initial frame prior to any processing. (b) Initial frame with reference square and corners pinned. (c) Initial frame with blurring applied. (d) Initial frame with threshold applied. (e) Later frame prior to any processing. (f) Later frame after low-pass filter in R. (g) Later frame with areas of interest numbered. Only the areas of interest with a centroid near the center of the image were used to calculate the perimeter and the total area of the smoldering region.

Table 1
Results of the Sieving Analysis on Chopped Needles

Size class (in)	Size class (mm)	Average mass (%)
> 0.25	> 6.3	1.2
> 0.185	> 4.7	2.5
> 0.131	> 3.3	47.7
> 0.1787	> 2.0	14.1
> 0.0469	> 1.2	10.9
< 0.0469	< 1.2	23.6
Sum		100

Results were averaged over three trials and reported as a percentage of sample mass

Contact with the peat layer was found to be crucial in scoping experiments because of the discontinuity of the longer needles.

Both fuel beds were conditioned overnight in a drying oven set to 70°C (160°F). This was done to provide a worst-case, wildfire scenario for the fuel moisture content. Moisture content of the whole needles, chopped needles, and peat were

Table 2
Ratio of Successful Ignitions to Attempts for the Three Air Flow Rates Tested

Fuel	1.7 m/s	1.4 m/s	1 m/s
Chopped needles	4/5 (1 marginal)	5/5	5/5
Whole needles/peat	5/5	5/5	5/5

checked separately using a Computrac Max2000XL moisture analyzer using 1 g samples dried at 145°C. The moisture content was considered final when the change in mass dropped below 0.1%/min. Moisture content was checked in the morning, after lunch, and at the end of each testing day. The moisture content was found to be around 4%, 3%, and 6% for the chopped needles, whole needles, and peat, respectively.

One brand of commercially available "fire safe" or "reduced ignition propensity" cigarettes was considered in this test series. A fresh pack was opened each day of testing to ensure their freshness.

2.2. Procedure

The wind was first set to the desired wind speed. This was measured using a hot wire anemometer placed in the middle of the outlet of the wind tunnel (12.5 cm and 4.25 cm from the walls). Three wind speeds were used in this test series based on some scoping experiments and the limitations of the apparatus: 1.0 m/s, 1.4 m/s, and 1.7 m/s. The halogen light was then plugged in and allowed to warm up sufficiently. The fuel to be tested was removed from the oven and weighed out in the sample holder. The actual weight of fuel used for each test was recorded. The remaining fuel was placed back in the oven. Since the laboratory space was not climate controlled (windows away from the experiment were opened to improve ventilation), the room temperature and humidity were noted prior to each test and ranged from 20.8°C to 28.9°C (69.4–84°F) and 17–49%. Note that all experiments were conducted inside in the summer on dry days. The sample was placed on the weighing platform under the work light. Logging of the sample mass was initiated. The cigarette was lit and drawn down 1 cm (marked ahead of time to ensure consistency, Figure 6) using a custom-built pumping apparatus. All cameras then began recording. The burning cigarette was then carefully placed by hand approximately in the middle of the fuel bed and was nestled down to ensure contact with the fuels. The cigarette was aligned with the wind direction, with the burning surface (coal or cherry) facing the wind. The cigarette was placed, not dropped, to ensure repeatability and the correct orientation with the wind and location within the fuel bed. Most tests with the chopped needles were allowed to burn for about 35 min and the peat/whole needle samples for about 16 min. This duration was deemed plenty sufficient to determine whether the ignition and spread were sustaining and independent of the burning cigarette (see discussion later for confir-

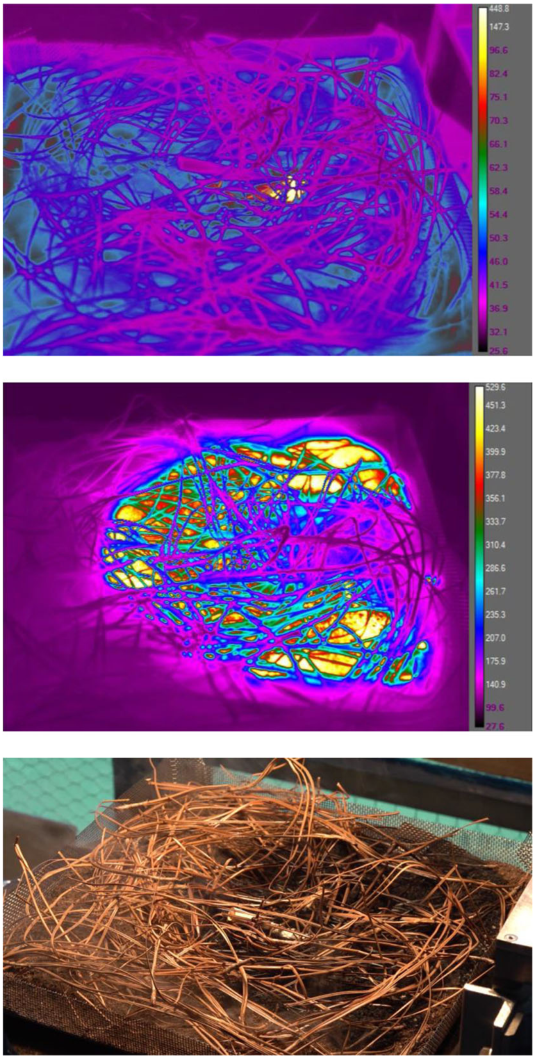

Figure 8. Scenes from Test #1 with peat and whole needles in 1 m/s wind. Top: IR image shortly after the placement of the cigarette. Middle and Bottom: IR and visual images shortly before the test was concluded showing clear signs of sustained smoldering away from a much cooled ignition region.

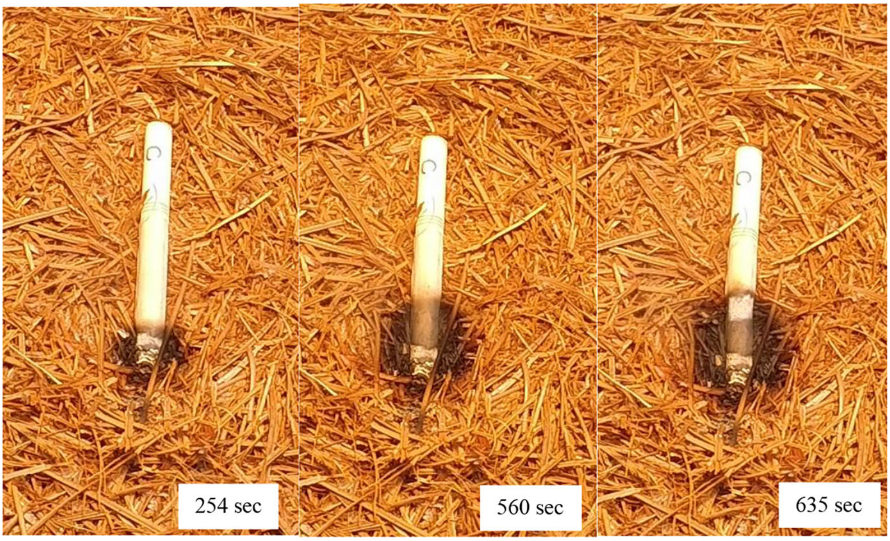

Figure 9. Cigarette burning on chopped needles in 1.7 m/s wind (Test #2) at three different times (in sec) from cigarette placement. In this case, the cigarette appears to self-extinguish, only to be reignited by the smoldering needles underneath.

mation). Once the test was complete, the sample holder was emptied, scrubbed with a wire brush, and allowed to cool completely before using it again. Five replicate tests for each condition and fuel were conducted.

2.3. Video Analysis

To evaluate the spread rates over the duration of the experiments, the video from the overhead Go-Pro camera was analyzed (the IR camera was positioned at too steep an angle for this analysis). An example of the image processing procedure is shown in Figure 7. The videos were first adjusted for the viewing angle using Adobe Premier. This was done by making a transparent square, then manually adjusted using the "corner pin" effect to match the square bottom of the sample holder as closely as possible (Figure 7b). Since the recordings were started before the cigarettes were placed, the videos were clipped to start once the hand that placed the cigarette is completely out of view. A clock was also added to the video for ease of processing later. An initial frame was also grabbed and saved separately to establish the pixel scale for that video. After some trial and error, it was found that the leading edge of the spreading front could be most consistently tracked by first blurring the video slightly to mask the influence of the shading and coloring of individual needles (Figure 7c). The videos were then converted into black and white using a thresholding level (Figure 7d). Both the blurring amount and threshold level were done manually for each test to best match the visual smoldering front. From there, the spread analysis could be conducted in R Studio [37] using the EBImage package [38]. A low-pass filter in EBImage was used to smooth the edges very slightly (Figure 7f). Then the computeFeatures.shape function was used to track the perimeter of the leading edge of the smoldering front as it spread across the fuel bed as well as calculate the total burned area (Figure 7g). Due to the creeping nature of smoldering spread, this analysis was conducted on one frame every four seconds. The diameter of the cigarette was used in each video as a measure of scale to convert pixels to cm. Naturally there will be some error generated due to these image processing and analysis methods, but the reported spread rates are not meant to be quantitative, but merely demonstrate the steady and sustained nature of the ignition and resulting spread.

Table 3
Burning Behavior of the Cigarettes in Tests with Chopped Needle Fuels

Wind speed [m/s]	Test	Approx. time of self-extinguishment [s]	Approx. reignition time [s]	Re-ignition delay [s]	Total cigarette burn time [s]
1.7	1	**NA**	**NA**	**NA**	**570**
	2	295	610	315	990
	3	365	1275	910	2100
	4	**NA**	**NA**	**NA**	**660**
	5	330	*NA*	*NA*	*330*
	Ave (stdev)	330 (35)	943 (470)	616 (421)	930 (695)
1.4	1	260	505	245	750
	2	365	485	120	555
	3	0	460	460	720
	4	60	225	165	690
	5	10	415	405	1260
	Ave (stdev)	139 (164)	418 (113)	279 (148)	795 (270)
1.0	1	210	*885*	*675*	*1080*
	2	145	740	595	1860
	3	460	515	55	720
	4	175	280	105	855
	5	375	595	220	870
	Ave (stdev)	273 (137)	603 (229)	330 (286)	1077 (456)

Note that all times provided are estimates and with potential errors of 10–20 s

Cases with "NA" are not included in the averages (ave) and standard deviations (stdev)

The Italic indicate tests where the cigarette was not fully consumed to ash (plus filter), and the Bold (and NA) indicate tests where the cigarette did not appear to self-extinguish at any point

Table 4
Results Video Analysis for Chopped Needle Fuel Beds

Wind speed [m/s]	Test	Final perimeter [cm]	Final area [cm^2]	Final time [s]	Cigarette burn time [s]	Average dr/dt (curve fit) [cm/hr]	Rough dr/dt (final radius/time) [cm/hr]	Average MLR/ burning area (last 10 min) [g/s-m^2]
1.7	1	14.56	16.88	1452	**570**	5.98	5.75	N/A
	2	54.21	233.9	2420	990	12.85	12.84	1.59
	3	61.86	304.55	2076	2100	17.4	19.75	2.08
	4	65.11	337.32	1900	**660**	19.77	22.51	2.67
	5	56.36	252.79	2128	*330*	16.03	15.17	2.94
	Ave (stdev)	50.42 (20.51)	229.09 (125.52)	1995 (357)	930 (696)	16.51* (2.89*)	17.57* (4.37*)	2.32 (0.60)
1.4	1	69.5	384.39	2248	750	20.42	17.71	1.82
	2	62.55	311.37	2128	555	16.94	16.85	3.58
	3	62.42	310.08	2136	720	17.22	16.74	2.61
	4	43.62	151.43	1949	690	13.92	12.83	2.33
	5	59.88	285.37	2151	1260	17.81	15.95	2.59
	Ave (stdev)	59.59 (9.62)	288.53 (85.12)	2122 (109)	795 (270)	17.26 (2.32)	16.01 (1.89)	2.59 (0.64)
1.0	1	47.85	182.17	2136	*1080*	14.07	12.83	0.78
	2	78.17	486.25	2132	1860	22.08	21.01	2.75
	3	25.50	51.74	2180	720	6.32	6.70	0.78
	4	68.39	372.17	2188	855	18.33	21.19	2.91
	5	38.27	116.53	2104	870	9.69	10.42	0.97
	Ave (stdev)	51.64 (21.57)	241.77 (181.74)	2148 (35)	1077 (456)	14.10 (6.36)	14.43 (6.47)	1.64 (1.09)

*The marginal test with 1.7 m/s wind was excluded from the average values

The Italic indicate tests where the cigarette was not fully consumed to ash (plus filter), and the Bold indicate tests where the cigarette did not appear to self-extinguish at any point

3. Results

Table 1 shows the average results of the sieving process for the chopped needles as a percentage of the total mass. As shown, the majority of the needles were broken into pieces smaller than 4.7 mm (0.185″), with a significant portion smaller than 1.2 mm (0.0469″). These small sizes ensured contact with the cigarette and simulated the partially decomposed layer (Oe) between the freshly fallen needles (Oi) and the humus layer (Oa) [39]. This fuel stratum has long been thought to be particularly receptive to ignition, as demonstrated in the earlier work examining cigarette ignition potential by Countryman [23].

Table 2 details the ignition observations. As in ASTM Standard E1353-21 [40], ignition of the fuel bed was considered successful if the smoldering front propagated sufficiently away from the cigarette. For example, Figure 8 shows a test conducted with the peat and whole needle bed in 1 m/s wind. The top image is shortly after the cigarette was placed in the fuel bed. The images in the middle and on the bottom are after about 16 min, shortly before the test was ended. The IR footage clearly shows a sustained smoldering front propagating away from the now much cooler ignition location. In many cases, "daylight" could be seen underneath the fuel bed where most of the fuel was consumed, particularly in the middle where the cigarette was initially placed (see Sect. 4.2.1 for further discussion of the three-dimensional nature of the spread). As Table 2 details, all tests but one demonstrated such ignition and spread that continued until the test was concluded (either after 35 min for chopped needles or 16 min for the peat/whole needle samples). It is thought that the one exception (the very first test conducted) was a marginal ignition because proper contact with the fuels was not achieved. Scoping tests with unconditioned fuels, without the heat lamp, and in a cooler lab environment were less successful, requiring higher airflow velocities with more frequent marginal ignitions. At the conclusion of the test series above, one additional test with conditioned chopped needles and heat lamp without any wind still clearly ignited. This indicated great sensitivity to fuel conditioning and environmental conditions and confirms the importance of these variables to successful ignition that was seen in previous work with non-FSCs [20–25].

4. Discussion

4.1. Self-Extinguishment and Reignition of Cigarettes

Though in some cases it is difficult to discern (especially in the beds with whole needles as they tended to block sight of the cigarette at times), it appeared that roughly 6 of the 30 cigarettes used may have burned their full length without extinguishing at any point. This amounts to 20%, which is less than the requirement to qualify as "fire safe." Four of the six cases where the cigarette burned fully were in the peat/whole needle beds, possibly because they tended to rest slightly downward to horizontal (see Figures 5 and 8), so buoyancy may have been providing extra airflow through the cigarette. Regardless of the fuel bed, 5 of the 6 cases that didn't self-extinguish occurred when the wind speed was at the highest setting (1.7 m/s), suggesting that increasing forced air flow prevents fire safety measures from working as well.

Interestingly, in many of the cases where self-extinguishment was suspected, the smoldering front in the cigarette seems to extinguish when it hit the bands of low permeability paper. However, the substrate underneath had already ignited, and the smoldering substrate then reignited the cigarette on the other side of the bands. This behavior is illustrated in Figure 9 which shows the same cigarette at three different times of the experiment. In this particular example, consumption of the cigarette paper stalled about 5 min (295 s) into the experiment. The needles underneath continued to spread for about another 5 min (i.e. 610 s into the test) before reigniting the filter paper 8–10 mm past where the cigarette initially self-extinguished. In other words, the cigarette appeared to be extinguished for five minutes before being reignited and burning until it was completely consumed (ash with filter). Table 3 below lists the estimated times that the cigarettes self-extinguished and reignited for all tests in chopped needle beds. However, these are just approximate values (with errors likely on the order of 10–20 s for the self-extinguishment time) since they are visual estimates from the videos. By watching the playback at an accelerated rate, the self-extinguishment time was estimated using best judgement for when the smoldering front appeared to stall. The re-ignition time was estimated as the time the paper visibly reignited at a point beyond the initial smoldering front. Unfortunately, these estimates were very difficult to make with the peat and whole needle beds as the needles often obscured the smoldering front of the cigarette, so they are not provided for these fuels. Also listed in Table 3 is the final cigarette burnout time, which is determined either by when the cigarette appears completely consumed (ash plus filter) or when it self-extinguishes with no further reignition (some paper wrapping appears to remain, albeit notably discolored). Though examining the average values may suggest some trends, the standard deviations are quite large in some cases, so differences between the various windspeeds were statistically verified by conducting two-tailed heteroscedastic t-tests ($p < 0.05$ for significance). Though technically no p-values are lower than the threshold for significance, assigning large values of the self-extinguishment time (e.g. 1000 s or the total cigarette burn time) for the two cases when self-extinguishment did not occur results in a statistically significant difference for the self-extinguishment time between the tests at 1.7 m/s and 1.4 m/s (though not between 1.7 m/s and 1.0 m/s). Otherwise, no statistically significant differences are seen in the cigarette burning parameters with wind speed for the conditions tested here. This dissociation between the self-extinguishment of the cigarette and its ability to still ignite a substrate is in line with what has been observed in the literature with soft furnishings and fabrics [15–19].

4.2. Sustainability of Fuel Ignition

As further confirmation that sustained ignition and smoldering spread were produced by the cigarettes, a simple analysis is performed with the mass loss data and video footage. Unfortunately, automated video analysis of the peat and whole needle fuels was extremely difficult due to the smoldering front of the peat layer propagating at a much faster rate than in the needles. When looking from the top down, the uncharred needles disrupted the continuous edge of the smoldering peat below (see Figure 8 for example) and the automated procedure would fail. For this reason, the videos from only the chopped needle fuel beds were fully analyzed. In the sections that follow, the analysis of the mass loss rates and spread rates will be presented.

4.2.1. Mass Loss Rates Mass loss rates were calculated by taking the derivative of the spline fit of the mass. Figure 10 shows representative results for the five replicates of the chopped needle bed in 1.4 m/s wind.

The burning behavior was quite interesting and clearly exhibited three-dimensional spread. The smoldering front seems to have initially spread downward, then horizontally. This was seen visually as the chopped needles would noticeably char within 10–20 s after the cigarette was placed, indicating minimal smoldering ignition delay time. The needles directly underneath the cigarette would char and smolder as the cigarette continued to burn, but the perimeter of the smoldering front in most cases couldn't be distinguished from the cigarette for the first minute or two of each experiment. Since relatively significant mass loss rates were measured during this period with little change in observed perimeter, it is likely that the smoldering front

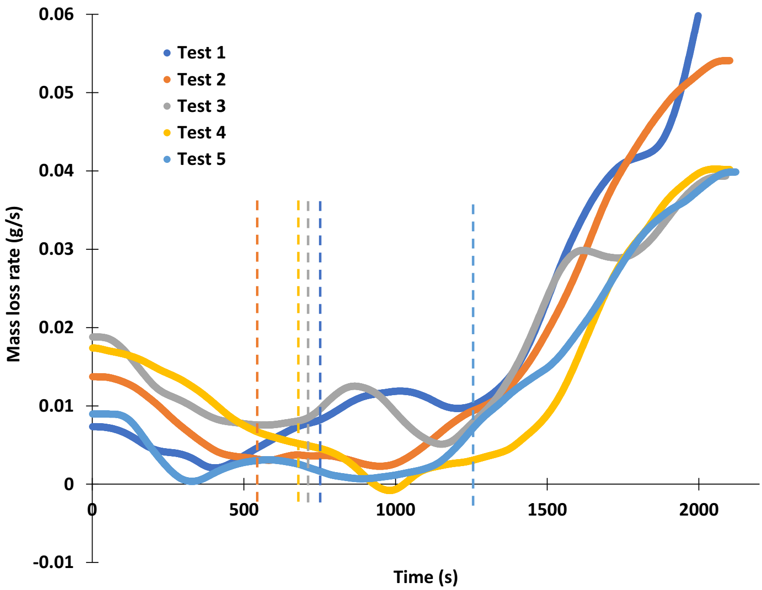

Figure 10. Mass loss rates for all five replicates of chopped pine needles with 1.4 m/s wind. Vertical dashed lines indicate the approximate time of cigarette extinguishment.

is propagating downward during this initial phase (see Figures 11 and 12). Additionally, initial mass loss rates may have been greater because of the influence of the cigarette. As the tests would progress, daylight was often seen below the sample holder in the region near ignition by the time the front spread significantly away from the cigarette (Figure 12). As the perimeter grew and the smoldering front reached the bottom of the fuel bed, the mass loss rate seemed to accelerate because of the increased reaction area and the increased availability of oxygen. This increase in burning rate with time is also seen in smoldering furniture experiments, where the burning rates after 30 min can be significantly larger than in the first half hour [41]. Shown in Figure 10 is also the approximate time that the cigarette extinguished in each experiment (see also Table 3 and 4). As discussed earlier, note that in most cases, this is the time that the cigarette appears fully consumed (ash plus filter), as most cases appear to self-extinguish, only to reignite and continue burning sometime later. It is clear that the acceleration in burning rate occurs after the cigarette fully extinguished in all cases so the cigarette is clearly not contributing to the continued smoldering propagation.

When the mass loss rates are normalized by the "burning area," i.e. the instantaneous perimeter of the smoldering front found from the video footage multiplied by the fuel bed depth (2.5 cm for chopped needles), the normalized burning rates do level off to relatively constant levels after the cigarettes are observed to extinguish. Figure 13 demonstrates this trend for the chopped needle bed experiments in 1.4 m/s wind, again with the vertical dashed lines indicating the approxi-

Figure 11. Still photos taken from chopped needle test in 1.7 m/s wind (Test #4). Top: Image taken 1 min into test showing very quick ignition of the needles. Middle: Image taken 8 min into the test showing that the initial spread of the smoldering front is largely along the length of the cigarette, before spreading in a more uniform, circular fashion. Bottom: Image taken 21 min into the test showing considerable smoke and the cigarette sunken down into the remnants of the fuel, indicating three-dimensional burning.

mate time that the cigarette fully extinguished. As indicated in Table 4, the average normalized burning rates over the last 10 min of the experiments are between 0.78 g/s-m^2 and 3.58 g/s-m^2, and do not appear to change significantly with wind speed. Here again, this insensitivity to wind speed was statistically verified by con-

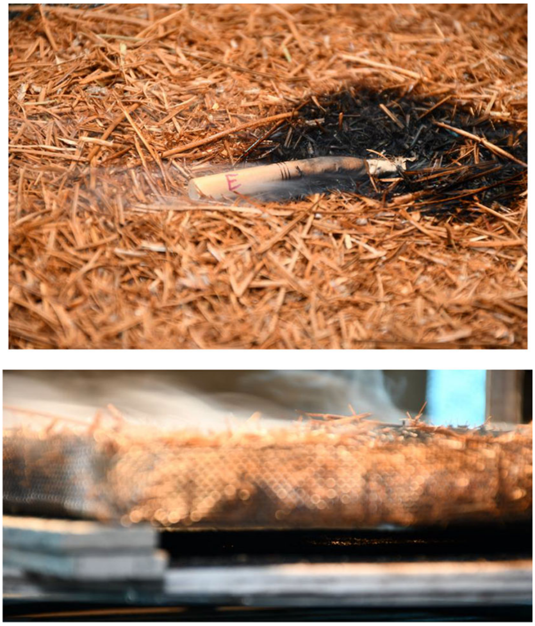

Figure 12. Still photos taken from chopped needle test in 1.7 m/s wind (Test #3) indicating three-dimensional burning. Top: Image taken 20 min into test showing the partially burned cigarette sagging down into the divot made by the consumed needles. Bottom: Image taken 30 min into the test showing that enough fuel has burned out in the center for the light from the lamp to show through the fuel bed and onto the weighing platform.

ducting a two-tailed heteroscedastic t-test ($p > 0.05$ in all cases). Similar burning rates were reported by Christensen et. al in peat (4–5 kg/hr-m^2 or 1.1–1.6 g/s-m^2) [42] and in cotton batting (1.2 g/s-m^2) [41, 43].

4.2.2. Spread Rates The lateral spread rate of the smoldering front in the chopped needle beds was also estimated from the video analysis. For this analysis, it was noted that even though these tests were conducted with a wind, the smoldering front did not have a dramatic tendency to spread in a preferential direction. In other words, the smoldering fronts were largely circular, regardless of the wind speed. The spread rates were then calculated two ways. The first was to track the total burned area with time, then calculate the average radius for that area assuming a circular shape. A curve fit was conducted on this radius as a function of time, and the spread rate was found as the numerical derivative of the curve fit. The results of this analysis for the chopped needle beds in 1.4 m/s wind are shown in Figure 14. The vertical dashed lines indicate approximately when the cigarette fully extinguished in each test. The change in radius with time (dr/dt), or spread rates, are shown here to either level off at a constant non-zero rate or continue to

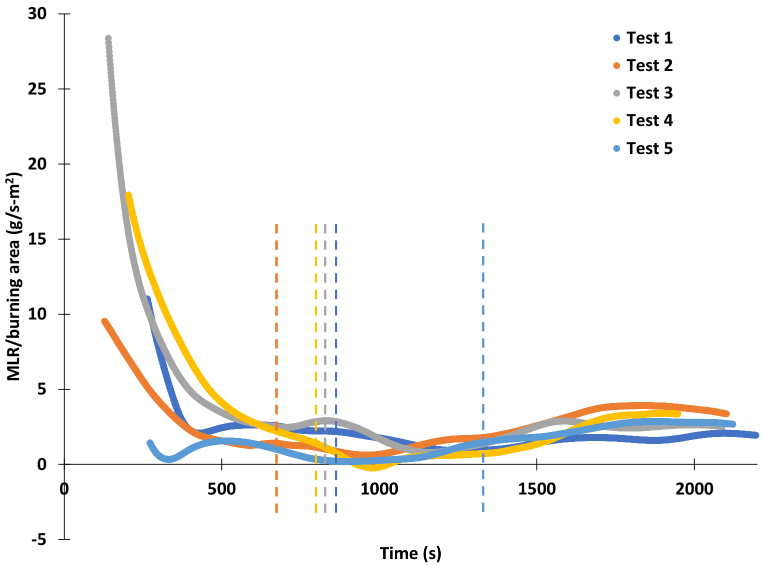

Figure 13. Mass loss rate normalized by the instantaneous burning front area (perimeter multiplied by fuel bed depth) for chopped needle beds under 1.4 m/s wind. Vertical dashed lines indicate approximate cigarette extinguishment.

accelerate well after the cigarette has fully extinguished, confirming once again that the smoldering spread is self-sustaining.

An alternative, simplified approach to calculating the average spread rate is to simply find the final radius of burned area (again assuming a circular burned region) and divide by the testing time. The average values of the first approach are compared in Table 4 to those of the simple second approach for all wind velocities. As shown, both methods produce very similar average spread rates. Also note, that here too, there is no statistical difference in average spread between tests with different wind velocities ($p > 0.05$ in all cases). Typical smoldering spread rates in the literature for many materials are around 0.5–3 mm/min (3–18 cm/hr) in no wind conditions [41]. Literature values for reverse smoldering rates appear relatively insensitive to wind speed for the range of wind speeds tested here [41, 42], while forward smoldering rates in cellulose insulation and peat can be twice the no-wind spread rate for the wind speeds examined here [42, 44] (for flow over the surface). Thus, the average spread rates found here are consistent with literature values for smoldering peat with wind conditions.

As the simplified approach to calculating an average spread rate seems to produce reasonable values, it was applied to the peat and whole needle beds as well. The results are shown in Table 5. Note that the final burned areas were found by manually blocking off the unburned regions of the fuel bed in the last frame of the video, and not with the automated procedure used with the chopped needle beds. This was done with the help of the "magic select" tool in Paint 3D before

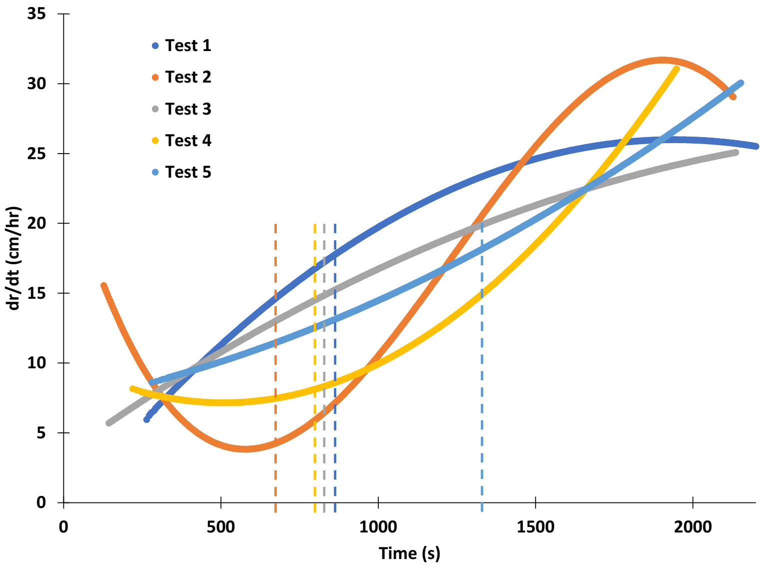

Figure 14. Change in radius of burned area (assuming circular burned region) over the testing period for chopped needle beds under 1.4 m/s wind. Vertical dashed lines indicate approximate cigarette extinguishment.

using the R-Studio code developed above to calculate the final area and perimeter. Though higher than in the chopped needles, sustained smoldering spread at rates consistent with those in the literature are seen here as well for relatively thin layers of dry peat smoldering in wind conditions. Here again, the spread rates at different wind speeds are not statistically significant ($p > 0.05$ in all cases).

4.3. Interpretation and Application

Even though it was successfully demonstrated that "fire safe" or "reduced ignition propensity" cigarettes can indeed ignite wildland fuels, it is important to understand the limitations of the tests conducted in this work. In particular, the worst-case scenario for wildfire conditions was chosen. As noted earlier, scoping tests with unconditioned fuels were not as successful, indicating the sensitivity of these results to fuel and environment conditions. As part of our worst-case scenario, the fuels were prepared in such a way to make them as receptive to ignition as possible by breaking them into smaller pieces to simulate the surface fuels between the freshly fallen needles and mineral soil. Obviously, not all discarded cigarettes will find their way into such a receptive fuel bed. The fuels were also dried to moisture contents between 3% and 6%. Dead fine fuel moisture contents (1-h fuel[2]) of 3–

[2] Note that wildland fuels are often characterized by size into 1-h, 10-h, 100-h, or 1000-h fuels that are defined based on the time lag required for the moisture content to reach equilibrium with the environment [45, 46].

6% are expected in sunny weather with relative humidities between 15% and 40% [46, 47]. Even lower fuel moisture contents can be achieved in more extreme fire weather. For example, 38°C (100°F) and 10% relative humidity will result in fine fuel moisture contents down to 2% [46, 47]. Even larger, 10-h and 100-h fuels can have moisture contents in this range [48]. For example, on August 16, 2020, the August Complex Fire (which burned over 417,000 ha (1,032,648 acres) in total [49]) reportedly experienced 10-h fuel moisture contents of 2.97% and 100-h fuel moisture contents of 5.96% [48]. Though what is considered "unusually low" fuel moisture content can vary with local vegetation and conditions, general guidance provided to wildland fire fighters is that fine fuel moisture contents between 5% and 7% are associated with very high ignition probabilities, rapid buildup, and loss of control, and fine fuel moisture contents below 5% are considered critical fire conditions [50].

Another consideration of these tests is that the laboratory environment was unconditioned. This could influence the moisture content of the fuels as the experiments progressed. This is especially true for the chopped needle beds as these experiments were allowed to run for 35 min. Given the measured conditions of the lab environment, the estimated highest equilibrium moisture content would have been about 7% for 21°C and 49% RH [47, 50] if the fuels had sufficient time to respond to the lab environment. The needles and peat are considered 1-h fuels, which are, by definition, expected to reach 63% of their final moisture content in an hour [45, 46]. Therefore, for a 35-min test, the fuels would not fully equilibrate to the unconditioned room environment. The additional heat from the overheat lamp may have helped to minimize this effect as sunny conditions are known to result in lower fuel moisture contents than cloudy conditions [46, 50]. However, some increase in fuel moisture content certainly occurred during the experiments, which for any somewhat long-duration smoldering experiment is inevitable. Note that the increase or steadying in burning rate (Figure 13) and spread rate (Figure 14) occurs even though the moisture content of the fuels likely slightly increased over the duration of the tests.

These experiments also tested only one species of pine needle using only one brand of commercially available cigarette. Certainly, different behavior could be expected from different fuels, such as grass, other needle species, or leaves. These other fuels will have a different bed structure that could influence their ignition susceptibility. For example, Countryman [23] showed that simply dropping a cigarette into standing tall grass would not produce a successful ignition because the cigarette tended to hang up off the ground in the sparse grass blades and the burning end of the cigarette didn't contact enough fuel. On the other hand, fuel beds of short needles, such as from fir or spruce trees, however, will naturally be more like the chopped needle beds tested here. Cigarette brand may also influence the results. Other brands of cigarettes may have different physical characteristics that are known to affect their ignition potential, such as circumference or tobacco density [8]. The cigarettes used in this study had bands of low permeability paper along their length. Other cigarette brands may have more frequent or wider bands that could extinguish the cigarette sooner, potentially before the wildland fuels ignite. Other cigarettes may employ entirely different strategies to satisfy the

Table 5
Results Video Analysis for Peat and Whole Needle Fuel Beds

Wind speed [m/s]	Test	Final perimeter [cm]	Final area [cm^2]	Final time [s]	Cigarette burn time [s]	Rough dr/dt (final radius/time) [cm/hr]
1.7	1	2.07	479.78	1127	**480**	39.48
	2	1.87	378.17	991	**435**	39.86
	3	1.80	401.66	968	435	42.05
	4	1.58	337.65	965	*600*	38.68
	5	1.77	420.24	981	**300**	42.44
	Average (stdev)	1.82 (0.18)	403.50 (52.63)	1006 (68)	450 (108)	40.50 (1.66)
1.4	1	1.50	307.12	916	*450*	38.86
	2	1.64	383.91	968	570	41.11
	3	1.75	373.74	968	540	40.56
	4	1.45	282.23	993	*435*	34.36
	5	1.96	490.08	1129	570	39.83
	Average (stdev)	1.66 (0.21)	367.41 (81.01)	995 (80)	513 (66)	38.94 (2.70)
1.0	1	1.36	238.61	952	**375**	32.96
	2	1.77	401.63	966	525	42.14
	3	1.89	432.66	933	720	45.28
	4	1.95	494.18	958	*450*	47.13
	5	1.14	108.70	950	660	28.74
	Average (stdev)	1.62 (0.36)	349.56 (133.56)	952 (12)	546 (143)	39.25 (8.01)

The Italic indicate tests where the cigarette was not fully consumed to ash (plus filter), and the Bold indicate tests where the cigarette did not appear to self-extinguish at any point

requirements to be certified "reduced ignition propensity" which could change their ability to ignite wildland fuels.

In these tests, the cigarette was placed on the top of the fuels to mimic if the cigarette is simply dropped, but there may be situations where the cigarette is better sheltered from the wind. For example, if there is an attempt to extinguish the cigarette by tamping it into the duff or soil, or perhaps dropping it and using one's foot to stomp on it or conceal it under nearby material. This could reduce the heat losses experienced by the cigarette and bring it in better contact with flammable wildland fuels, increasing the potential for ignition.

The wind speeds used in these tests were commensurate with velocities used in other small-scale experiments [42, 51, 52]. For example, Christensen et al. used 0.86 m/s in [42] and noted that a higher windspeed resulted in the movement of the fuel particles (peat) in the wind. It is interesting that in the tests conducted here, no statistical trend in the cigarette or wildland fuel burning behavior was noticed. This could be partly due to the variability in the experiments due to the stochastic nature of smoldering in discrete, non-uniform particles. Additionally, the analysis methods used for the spread rates certainly adds an unknown amount of uncertainty to the results as best judgement was used to manually determine the appropriate amount of blurring and brightness thresholds for each individual experiment. However, the lack of statistical trend was not limited to just spread rates, but also occurred in the mass loss rate of the wildland fuel and the burning behavior of the cigarettes. Perhaps many more replicate tests would help clarify any potential trends, but finding such trends was not the goal of this study. The analyses on the mass loss rates and spread rates were only provided to document that the smoldering spread in the wildland fuels was independent of the ignition source and was sustained. On the other hand, the lack of variation with wind speed may also be a somewhat physical result. Though Christiansen et al. [42] only used one wind speed, they noted that there was minimal change in smoldering peat spread rates in the direction lateral to (horizontal or flanking spread) and into the wind (opposed or backing spread) compared to the no wind case. Only when the fuels were completely dry or when the spread was with the wind (forward or heading spread) was a difference seen. Other materials also demonstrate an insensitivity of reverse smoldering rates to wind speed [41]. In [41], it is also pointed out that there is a fundamental difference between smoldering spread response to wind flowing *over* a fuel bed versus *through* the fuel bed. Forward smoldering rates with flow through the bed are much less sensitive to wind speed than if the flow is over the fuels. While the experiment setup here intended to have the air flow over the surface of the fuels, this may not have remained the case as the tests progressed. As the center burned out, the portion of the fuel bed experiencing forward smoldering may have been exposed to more flow through the bed, not just over it. Additionally, in [41] it is noted that a modest wind can increase the propensity of ignition, but high winds will reduce it, indicating a non-monotonic behavior with wind speed.

While outside of the scope of this work, fully elucidating the effect of all these potential variables (fuel type, fuel condition, fuel moisture content, wind speed, cigarette brand, cigarette placement, etc.) is necessary to fully understand the ignition potential and to identify the limiting conditions.

One final note should be made on interpreting these results (and other small-scale tests) in practical situations. The windspeeds reported here are the windspeeds measured just above the fuel bed. It is important to remember that this wind is different from that reported by weather forecasts, which is typically measured 10 m or 20 ft above the ground. Not only does a boundary layer form above the Earth's surface, any canopy or vegetation can further slow the wind down on the ground. For example, as shown in Table 6, using the estimates provided by Albini and Baughman [53] (which are used to calculate the mid-flame windspeed in wildland fire spread calculations such as in [54]), a 1.7 m/s wind measured on the ground below a dense canopy of shade tolerant trees that are 55 m (180 ft) tall would correspond to a 6 m (20 ft) windspeed of 20.2 m/s or 72.9 km/hr (45.2 mph) wind as reported in a weather report. So, while the wind velocities tested seem quite low, they do correspond to winds encountered in realistic wildfire scenarios.

Table 6
Estimates Following Albini and Baughman [53] of the Practical Windspeeds (km/hr) (as Reported in Weather Forecasts) that Correspond to the Wind Tunnel Test Conditions

	Stocking level	Shade tolerant			Shade intolerant		
Wind tunnel speed		Young (12 m)	Mature (30 m)	Pacific (55 m)	Young (12 m)	Mature (30 m)	Pacific (55 m)
1 m/s	Dense	23.2	31.9	42.9	16.4	18.4	24.7
	Open	12.3	17.1	23.1	10.8	14.5	19.5
1.4 m/s	Dense	32.5	44.6	60.0	22.9	25.7	34.5
	Open	17.2	24.0	32.3	15.2	20.3	27.2
1.7 m/s	Dense	39.5	54.2	72.9	27.8	31.2	41.9
	Open	20.9	29.1	39.2	18.4	24.7	33.1

5. Conclusions

This study set out to only answer the simple question of whether or not FSCs could ignite wildland fuels, which it did with a resounding "yes." However, there is bountiful work that remains to fully explain and understand the phenomena. The conditions chosen here were selected to be representative of the worse-case scenario in wildfire conditions. Specifically, hot, sunny, and windy conditions with very dry fuels that were prepared to be as receptive to ignition as possible. In scoping experiments, we were less successful with wetter fuels and without the solar heating, so much work remains to understand the limiting conditions for ignition via a FSC in natural fuels. Further work should be performed to examine different fuels, fuel loadings, moisture content, atmospheric conditions (external heat flux, ambient temperature and humidity), wind speeds, cigarette brands, cigarette drawdown length, cigarette orientation relative to the wind, cigarette depth within the fuel bed, etc.

Acknowledgements

The authors would like to thank Jonathan Butta of the ATF Fire Research Laboratory for sharing his knowledge and experience with FSCs that really helped get these experiments moving. This research was funded by the Certified Fire Investigator Program of the Bureau of Alcohol, Tobacco, Firearms and Explosives and the National Fire Decision Support Center.

Data availability

All data not included in the paper itself is available upon reasonable request from the corresponding author.

Declarations

Conflict of interest All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript. The first author is an Associate Editor for Fire Technology Journal but did not participate in the review process in any way.

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